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Protoneutron stars with kaon condensate

T. Tatsumi ^{*}and M. Yasuhira

Department of Physics, Kyoto University, Kyoto 606-8502, Japan

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Abstract

A new formulation is presented to treat fluctuations around the kaon condensate. Equation of state (EOS) is given for isothermal and isentropic cases in the heavy-baryon-limit (HBL). The coexistent phase appears in the latter case. The mass-radius relation is given for protoneutron stars and the possibility of the delayed collapse is discussed.

1 INTRODUCTION

There have been extensively studied for years about kaon condensation and its implications on neutron stars at low temperature [1]. In 1994 Brown and Bethe proposed the low-mass black hole (BH) scenario, based on the large softening of EOS due to kaon condensation [2]. It is produced as a consequence of the *delayed collapse* from a protoneutron star, different from the usual BH formation. This scenario should be very attractive in the light of recent observations on the mass of neutron stars, SN1987A or future observation of neutrinos associated with supernova explosions. Some numerical simulations based on the general relativity have been already performed for

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the delayed collapse [3, 4]. In ref.[3] they studied the delayed collapse by using the EOS of kaon condensed phase at $T = 0$, though temperature is very much increased there. Also neutrino trapping is another important factor to be considered for protoneutron stars.

There have been some attempts to treat thermal fluctuations in relation to kaon condensation [5], but there seems to be no successful theory on the basis of chiral symmetry. Recently we have proposed a formalism to treat this problem [6], in relation to protoneutron stars. Here we briefly explain how our formalism gives the thermodynamic potential, and show some results about EOS and structure of protoneutron stars.

2 THERMODYNAMIC POTENTIAL

The kaon condensed state can be described as a chiral-rotated one from the meson vacuum [7]; actually we can discuss kaon condensation in almost model-independent way within the mean-field approximation. However, if we intend to study the phenomenon further by taking into account the effect of fluctuations, it is useful to invoke the effective Lagrangian like the nonlinear sigma model.

2.1 Path integral

We start with the partition function Z_{chiral} for the nonlinear sigma model \mathcal{L}_{chiral} ,

$$Z_{chiral} = N \int [dU][dB][d\bar{B}] \exp[S_{chiral}^{eff}], \quad (1)$$

with the effective action,

$$S_{chiral}^{eff} = \int_0^\beta d\tau \int d^3x [\mathcal{L}_{chiral}(U, B) + \delta\mathcal{L}(U, B)], \quad (2)$$

where $\delta\mathcal{L}(U, B)$ is the newly-appeared symmetry-breaking (SB) term due to the introduction of chemical potentials [6]. In evaluating the integral (1), we introduce the local coordinate around the condensate on the chiral manifold, which is equivalent with the following parametrization [6],

$$U \equiv \xi^2 = \zeta U_f \zeta (\xi = \zeta U_f^{1/2} u^\dagger = u U_f^{1/2} \zeta), \quad \zeta = \exp(\sqrt{2}i\langle M \rangle / f), \quad (3)$$

where $\langle M \rangle$ is the condensate, $\langle M \rangle = V_+ \langle K^+ \rangle + V_- \langle K^- \rangle$, with $K^\pm = (\phi_4 \pm i\phi_5)/\sqrt{2}$, $\theta^2 \equiv 2K^+K^-/f^2$ and $V_\pm = F_4 \pm iF_5$, while $U_f = \exp[2iF_a\phi_a/f]$ means the fluctuation field. Accordingly defining a new baryon field B' by way of $B' = u^\dagger Bu$, we can see that

$$\begin{aligned}\mathcal{L}_{chiral}(U, B) = \mathcal{L}_0(U, B) + \mathcal{L}_{SB}(U, B) &\longrightarrow \mathcal{L}_0(U_f, B') + \mathcal{L}_{SB}(\zeta U_f \zeta, u B' u^\dagger) \\ \delta\mathcal{L}(U, B) &\longrightarrow \delta\mathcal{L}(\zeta U_f \zeta, u B' u^\dagger)\end{aligned}\quad (4)$$

Thus all the dynamics of kaons and baryons in the condensed phase are completely prescribed by the non-invariant terms $\mathcal{L}_{SB}, \delta\mathcal{L}$ under chiral transformation; it is to be noted that the meson mass is included in \mathcal{L}_{SB} and the Tomozawa-Weinberg term is in $\delta\mathcal{L}$.

2.2 Dispersion relation

The effective action for the kaon-nucleon sector can be represented as

$$S_{chiral}^{eff} = S_c + S_K + S_N + S_{int}, \quad (5)$$

where S_c is the previous classical-kaon action [1] and S_N the nucleon action discarded in HBL. The sum $S_K + S_{int}$ gives the effective kaon action,

$$S_K^{eff} = -\frac{1}{2} \sum_{n, \mathbf{p}} (\phi_4(-n, -\mathbf{p}), \phi_5(-n, -\mathbf{p})) D^{eff} \begin{pmatrix} \phi_4(n, \mathbf{p}) \\ \phi_5(n, \mathbf{p}) \end{pmatrix} + \dots, \quad (6)$$

with the inverse thermal Green function D^{eff} . Looking for the zeros in D^{eff} , we find two solutions E_\pm ; E_- corresponds to the Goldstone mode and exhibits the Bogoliubov spectrum,

$$E_-^2 \sim \frac{c_3}{2C^2} p^2 + \frac{p^4}{4C^2} + \dots \quad (7)$$

where C means an effective mass for kaons and c_3 the product of the charge density and the KK scattering length [6]. We shall see the importance of the thermal kaon loops due to the Goldstone mode. The origin of this Goldstone mode is easily understood by observing that the kaon-condensed state is no longer invariant with respect to the V -spin rotation, while the effective Lagrangian is still invariant. In other words, we can schematically say that the newly-appeared SB term $\delta\mathcal{L}$ completely cancels the original SB term \mathcal{L}_{SB} , and gives rise to a *new* spontaneous symmetry breaking (SSB) instead.

3 RESULTS

First we show EOS thus obtained for the isothermal and isentropic cases (Fig. 1). Since it exhibits the first-order phase transition (FOPT), we pre-

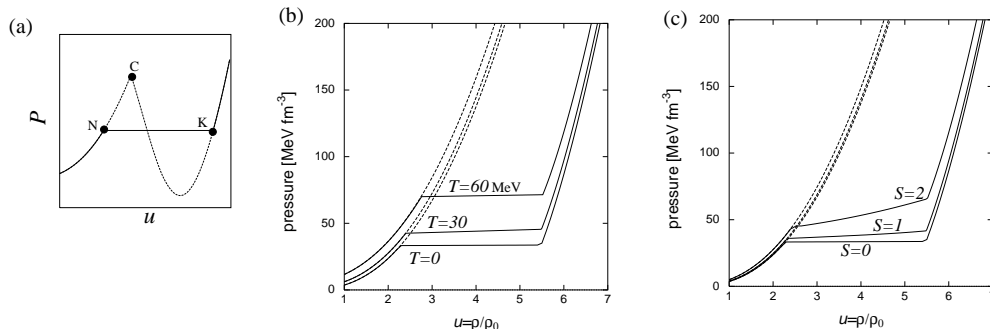


Figure 1: Sketch of EOS and graphical construction for the equilibrium curve in the isothermal case (a). EOS for the isothermal case (b) and the isentropic case (c).

scribe, for simplicity, the Maxwell construction by connecting the equal-pressure densities for the normal (N) and condensed (K) states. This means that there is no coexistent phase for the isothermal matter. On the other hand the coexistent phase appears in the isentropic matter due to the variation of temperature density by density. The magnitude of FOPT is so large that we shall see the existence of the gravitationally unstable region in the branch of neutron stars (see Fig. 2(b)). The effect of thermal fluctuations should be self-evident there.

For protoneutron stars, the isentropic situation should be more relevant. In Fig.2(a) we present the temperature profile inside for protoneutron-star matter the entropy $s = 1, 2$. It is a monotonically increasing function with respect to density, and takes the maximum value of several tens MeV at the center. The difference from no kaon case is rather small. In Fig.2(b) we depict the mass-radius relation for protoneutron stars with isentropic structure. The branch of protoneutron stars is clearly separated into two parts by the gravitationally unstable region. We can see that thermal effects are insufficient to support higher mass; on the contrary, the maximum mass is a little bit reduced at $T \neq 0$.

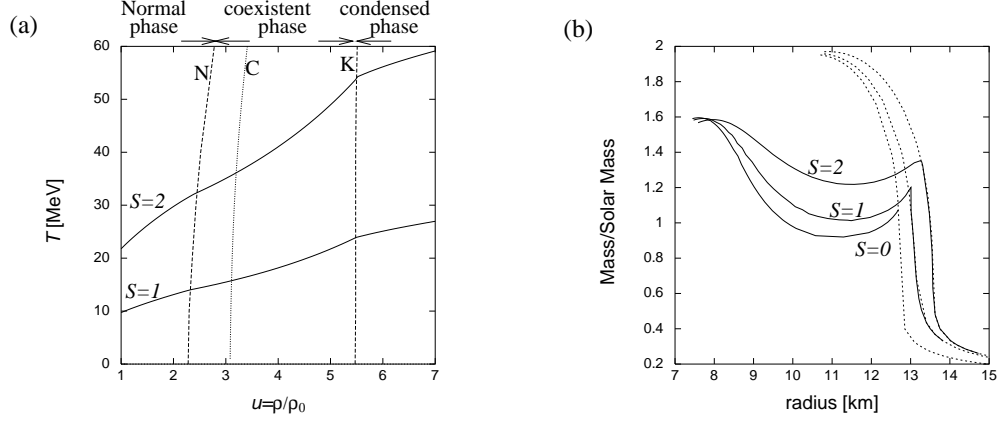


Figure 2: (a) Temperature profile of the kaon-condensed matter. (b) Mass-radius relation for protoneutron stars (solid lines). Positive slope region means the gravitationally unstable branch. The symbols N , C , K correspond to those in Fig. 1(a).

4 SUMMARY AND CONCLUDING REMARKS

A systematic formulation to include fluctuations around the condensate is presented by introducing the local coordinate on the chiral manifold. This procedure makes the aspect of chiral rotation prominent for the kaon condensation. Using this we obtained the dispersion relation for the kaonic mode; one is the Goldstone mode as a consequence of the SSB of the V -spin symmetry, while the other is a very massive mode.

The EOS is obtained, in the HBL, for the isothermal and isentropic cases, where the role of thermal kaons should be noted. The EOS exhibits FOPT and it might be interesting to see the appearance of the coexistent phase in the isentropic case. On the other hand, the temperature profile is little changed from that in no kaon matter. These results may be relevant for the delayed collapse during the initial cooling era, where neutrinos are no longer trapped. Hence it is interesting to observe how these results affect the collapsing process and the profile of the neutrino luminosity by dynamical simulations.

The maximum mass of protoneutron stars is around $1.6M_\odot$ and is not larger than that of cold neutron stars in this calculation, which suggests

more elaborate study is needed to include nucleon dynamics and the neutrino trapping for observing the delayed collapse.

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